FURTHER EXPERIMENTS ON THE MASS OF THE ELECTRIC CARRIER IN METALS

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Abstract

Inertia of the electric carrier in metals.—Although Tolman and Stewart had apparently demonstrated that the carriers in metals have approximately the same ratios of mass to charge as an electron, it was desirable to verify this result and if possible obtain a more accurate value for m/e by using an entirely different method. An *oscillating apparatus* was constructed, consisting of a copper cylinder $9\frac{1}{8}''$ long, $4''$ outside diameter and $3''$ inside diameter, attached to a brass torsion rod in such a manner that it could be oscillated about its axis with a frequency of about 20 cycles per second. Surrounding this copper cylinder was a coil, containing about 60 miles of No. 38 copper wire, which acted as the secondary of a transformer, and was connected to a vibration galvanometer through a specially designed three-stage amplifier. The tendency of the electrons in the oscillating copper cylinder to lag behind because of their inertia leads to an electromotive force, the effects of which were finally measured by the deflection of the vibration galvanometer, tuned to the frequency of the mechanical oscillations. This galvanometer deflection was then compared with that produced by the known electromotive force accompanying a transverse oscillation of the cylinder across the earth's magnetic field. The apparatus was mounted on a massive concrete pier in a special location 150 yards from the nearest electrical circuits, was constructed without the use of magnetic materials, and was driven by compressed air. The axis of the oscillating cylinder was set parallel to the earth's magnetic field to reduce accidental effects. The apparatus avoids the direct electric connections between moving and stationary parts, and the sudden stopping of a coil of wire, with the attendant chance of buckling and slipping of the wire, which were present in the apparatus used by Tolman and Stewart. The fact that the vibration galvanometer will respond only to the frequency of the desired effect is also important in eliminating accidental effects. *Mass of carrier in copper.* The average of 86 determinations of m/e is 5.2×10^{-8}. However since the means of the first 42 determinations and of the last 44, obtained with the cylinder earthed only through the concrete pier and specially earthed, respectively, are 5.97 and 4.35, and since the corrections for zero amplitude were large, these preliminary results are not regarded as demonstrating a difference between the ratio m/e of the carrier in copper and of an election in free space, 5.66×10^{-8}.

I. Introduction

The production of an electromotive force by the acceleration of a metallic conductor has apparently been demonstrated by the work of Tolman and Stewart,[1] who measured the pulse of electric current produced by suddenly stopping a coil of wire rotating around its axis.

[1] Tolman and Stewart, Phys. Rev. **8**, 97 (1916); **9**, 164 (1917).

Their experiments showed that this pulse of current was always in the direction which would be predicted on the basis of a mobile *negative* electron for the carrier of electricity in metals, and that the effective mass of this carrier in copper, silver and aluminum was not far different from the mass of a negative electron in free space.

The purpose of the work described in the present article has been twofold. In the first place it seemed desirable to obtain a new demonstration of this production of an electromotive force by the acceleration of a metal, using some method of attack as different as possible from that of Tolman and Stewart, in order to increase our certainty as to the reality of the effect. In the second place it seemed desirable to find a method of measurement which would eliminate certain accidental effects inherent in the earlier procedure and thus make possible a more exact determination of the mass of the carrier in metals. This is a matter of some importance since the earlier work indicated that the mass of a free electron in a metal is somewhat greater than the mass of an electron in vacuo, and if this could be shown to be true it might considerably increase our knowledge as to the inner constitution of metals and perhaps as to the nature of the electron itself.

As will be shown in the sequel, we have apparently again demonstrated the reality of the effect and have developed a method which shows possibilities of considerably greater accuracy than that of Tolman and Stewart. Owing, however, to the resignation of one of the experimenters from the staff of the Fixed Nitrogen Research Laboratory, time was not available to push this new method to such a point as to make certain whether or not the mass of the electron in a metal does differ from its mass in free space. Plans are being made for the continuation of these experiments at the California Institute of Technology where it is hoped this latter point can be definitely settled.

II. Description of Apparatus

In the experiments of Tolman and Stewart, it was felt that irregular accidental electromotive forces were most likely to arise either in the coil itself, because of such mechanical disturbances as slippage or buckling of the wire accompanying the jar of stopping, or at the binding posts for connecting the rotating coil with the twisting wires leading to the galvanometer, because of mechanical strains or temperature fluctuations at these points. For this reason, our new apparatus consisted of a single cylindrical shell of copper which could be oscillated around its axis with a frequency of about twenty cycles per second, and which was surrounded by a coil with many turns of fine wire, connected through an amplifying set to a vibration galvanometer. The oscillating cylinder thus acted as the primary of a transformer and the coil of fine wire as the secondary. In this way we applied a regular periodic acceleration to a solid shell of metal, instead of applying a sudden change in velocity to a coil of wire, and we furthermore eliminated the necessity of any direct electrical connections between moving and stationary parts of the apparatus.

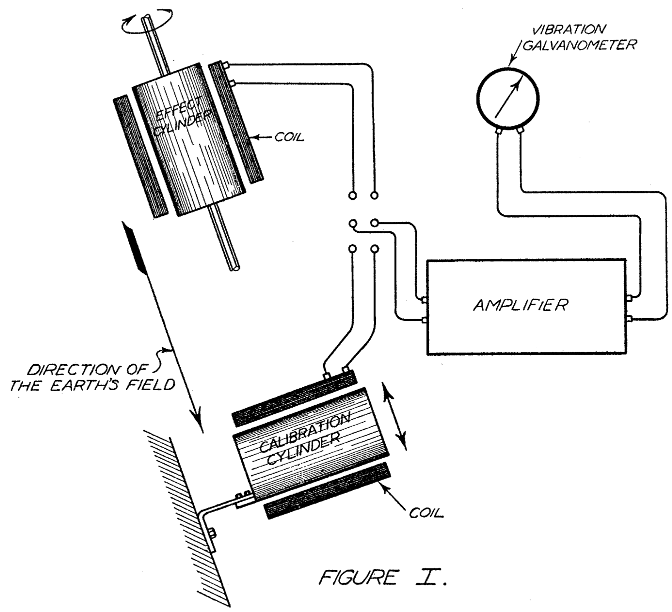

FIGURE I.

The general arrangement of the apparatus is shown schematically in Fig. 1. The potential produced in the secondary by the rotary oscillations of the "effect cylinder" was impressed on a three-stage amplifier, and the amplified current was sent to a vibration galvanometer tuned to the frequency of oscillation.

In order to calibrate the apparatus, a "calibration cylinder" was provided which was made to oscillate at right angles to its axis in such a way as to cut the lines of force of the earth's magnetic field, thus producing a known electromotive force which could be compared with that produced by the effect itself.

Various parts of the apparatus are shown in more detail in Fig. 2. The individual features of the apparatus are described at some length below, in order to make possible an intelligent criticism of the work.

The location.—Preliminary experiments with the apparatus were first carried out in one of the buildings of the Fixed Nitrogen Research

Laboratory. In this first location, however, the continuous accidental variations in electromagnetic conditions were found to be so great as to prevent successful measurement, since the vibration galvanometer was always in violent oscillation when connected through the amplifying set to the coil, even though the coil and cylinder were stationary. A part of this trouble was found to come from electric circuits which were used in the building, some of it, however, apparently came from high potential power lines which entered the Laboratory reservation near the building in question.

The trouble was very greatly decreased by removal to an isolated spot, one hundred and fifty yards from the nearest building with electric circuits, and considerably further from the high potential lines.

The concrete pier.—In order to reduce accidental effects due to motion in the earth's field it was desirable to set the effect cylinder with its axis of oscillation parallel to the earth's magnetic field, and to have the apparatus mounted as solidly as possible. For this purpose we constructed a concrete pier with its northern face approximately parallel to the magnetic dip.

The pier which is shown in Fig. 2 had a total height of about seventeen

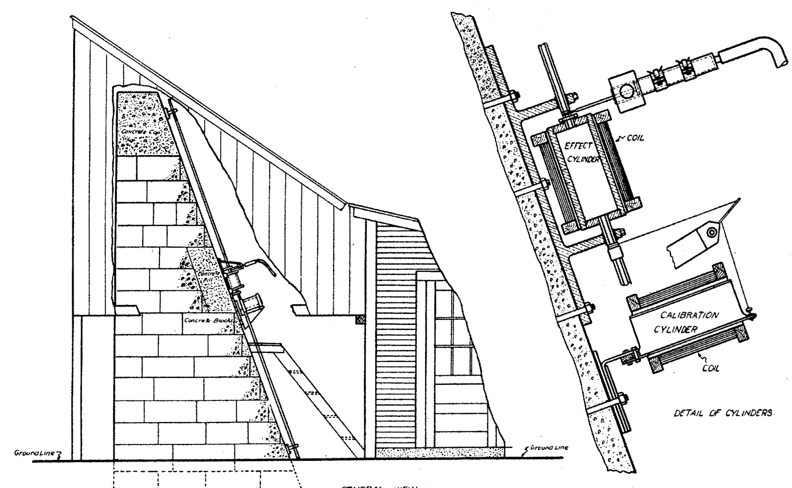

FIGURE II

feet, two feet being below ground. The base of the pier was seven feet from face to back, five feet wide at the face and three feet wide at the back. The cap of the pier was not quite two feet from face to back and three feet wide. It will thus be seen that the structure was quite massive and solid.

The concrete blocks were unfortunately not made from specially selected materials, but were of course free from iron reinforcement and all the bolts for fastening apparatus to the pier were of brass.

The oscillating system.—The most fundamental part of the apparatus was of course the effect cylinder whose rotary oscillations produced the effect to be studied. This was machined from a copper billet which was cast and then forged at the Washington Navy Yard. The material showed itself in the lathe to be homogeneous and of fine structure due to the forging process. The cylinder was $9\frac{1}{8}$ inches long, with an outside diameter of 4 inches and an inside diameter of 3 inches. The cylinder was provided with copper disks on the two ends as shown in cross section in the detail view in Fig. 2. These disks were $\frac{5}{8}$ inch in thickness and were sweated into place.

These disks formed the means of attachment for the rod the torsion of which provided the restoring force for the rotary oscillations. In order to eliminate magnetic effects due to torsion, this rod was made from special non-magnetic "Navy Brass" such as is used in the construction of torpedoes. The rod was hexagonal in cross section, $\frac{5}{8}$ inch from flat to flat. The distance from end to end between clamps was 14′ 10″, which made the period of oscillation about twenty cycles per second.

This hexagonal rod was provided with brass bushings 25/32″ in diameter on each side of the cylinder, which rested in brass bearings as shown in cross section in the detail, Fig. 2.

Since electrical means for keeping the system in oscillation were obviously ruled out, arrangements were made to drive it by compressed air. The simple air engine used for this purpose, is shown in the detail of Fig. 2, and consisted of a brass cylinder about one inch in inside diameter, provided with a very light brass piston and piston rod which acted on a brass pin set in a copper cross arm fastened across the top of the effect cylinder. The compressed air was admitted to the engine cylinder at the rear end, and this cylinder was slotted from the front end back approximately to the central position of the piston. Under these conditions, somewhat surprisingly, the engine would maintain oscillations without the necessity of any mechanical valves at all, air apparently escaping through the slots in such a way as to make the pressure more effective on the forward than on the back stroke. The front end of the cylinder was surrounded by a housing with a pipe which carried the escaping air away from the slots, thus reducing spurious effects which might arise from the periodic discharge of air in the neighborhood of the coil and incidentally reducing the noise. Compressed air for operating the engine was brought out in storage cylinders, pumped up to 3,000 lb pressure, one cylinder being sufficient for several hours of experimentation.

In addition to the effect cylinder which was oscillated around its axis, a calibration cylinder was provided, as stated above, which was placed with its axis at right angles to the earth's magnetic field and oscillated so as to cut the earth's field in such a way as to produce a reproducible electromotive force which could be compared with the electromotive force arising in the main cylinder from the inertia of the electric carriers.

This calibration cylinder is also shown in some detail in Fig. 2. It was fastened to the concrete pier by a brass bracket which was stiff enough so as to make the natural period of oscillation considerably higher than that of the effect cylinder. It was then driven from the main oscillating system by means of light weight, waxed, silken cords acting on a very light lever as shown in Fig. 2. In this way it was possible to drive the calibration cylinder with the same frequency as the effect cylinder, a matter of great importance since our vibration galvanometer was connected in such a way as to have very sharp tuning. It was shown by actual experiments, using smoked paper and styluses, that the two systems did move with the same frequency.

Two different calibration cylinders were used both made from drawn copper tubing, $3\frac{1}{2}''$ inside diameter and, except for the lips used for attachment of the bracket and cord, the same length as the effect cylinder. One of the calibration cylinders was made with $1/16''$ wall and the other with $1/32''$ wall.

The coils.—The coils which acted as secondaries both in the effect circuit and the calibration circuit were wound from No. 38 enameled copper wire. The windings had an inside diameter of approximately $4\frac{1}{4}''$, outside diameter of $5\frac{3}{4}''$ and a length of $7''$. They contained about 15 lb of wire which gave a length in the neighborhood of 60 miles and a resistance in the neighborhood of 180,000 ohms. The great length of wire was of advantage since the amplifier acted more as a potential detector than as a current detector.

One of these coils was placed around the effect cylinder and fastened as solidly as possible to the concrete pier, to avoid vibration in the earth's field, which would of course have produced accidental electromotive forces. Special experiments were made which led us to the belief that the coil as finally fastened did not have serious accidental electromotive forces from this source. The other coil was placed around the calibration cylinder. The two coils were distinguished as coil No. I. and coil No. II. and were interchanged from time to time. They were found to be so nearly of the same effectiveness that, taking other uncertainties into consideration, no allowance has been made in the calculations for a difference between these coils.

The amplifier.—Connection from the coils was made, through a double throw switch set in paraffin, to a specially designed amplifying set. This amplifying set is shown diagrammatically in Fig. 3. Since the frequency

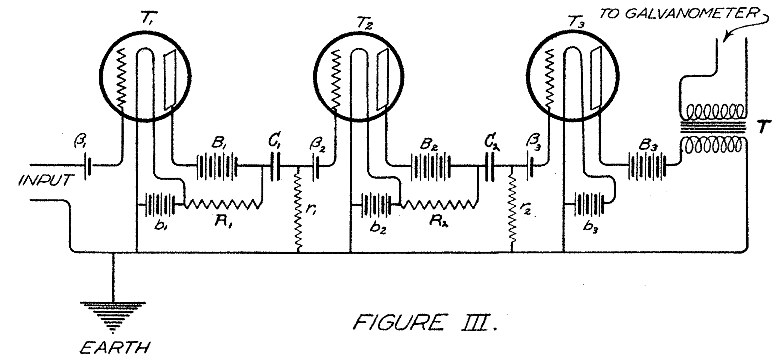

FIGURE III.

of the impressed electromotive force was low, resistance coupling instead of transformer coupling was used between the stages.

Tubes T_1 and T_2 for the first and second stages were furnished us by the courtesy of the Western Electric Co. They each had a voltage amplification constant of about thirty, and were operated with a filament heating current of 0.8 ampere. The first tube T_1 was specially selected as free from "noises." Tube T_3 for the last stage was a regular VT_1, U. S. Signal Corps tube, and was operated with a heating current of 1.1 amperes.

The batteries b_1, b_2, and b_3 for the filament heating currents were Edison six-volt storage batteries. The batteries B_1, B_2, and B_3 for the plate circuits were made from "flash light" cells, B_1 and B_2 giving approximately 140 volts, and B_3 60 volts. The grids were set approximately $1\frac{1}{2}$ volts negative with respect to the filaments by small dry cells β_1, β_2, and β_3.

The resistances R_1 and R_2 for the resistance coupling were Lavite resistances of 200,000 ohms each. The grid leaks r_1 and r_2 were $2\frac{1}{2}$ megohms. The condensers C_1 and C_2 had capacities of 0.5 microfarad each. The primary of the transformer T had an impedance of about 20,000 ohms (25$\sim$) and the secondary which was connected direct to the vibration galvanometer had an impedance of about 2,400 ohms (25$\sim$).

The vibration galvanometer.—The galvanometer was a Leeds and Northrup vibration galvanometer, provided with a specially light suspension so as to reduce the frequency to the desired value. It had a concave mirror which was illuminated by a single filament lamp, the distance from mirror to ground glass scale being 10′ 1″. The resistance of the galvanometer was 765 ohms, its impedance unknown.

III. Theory of the Experiment

The experiments consisted in measuring as nearly simultaneously as possible the amplitude of the rotary oscillation of the effect cylinder, the amplitude of the transverse oscillation across the earth's field of the calibration cylinder, and the two corresponding galvanometer deflections. These measurements were then followed by a "master" calibration in which the deflections produced by oscillating the effect cylinder itself transverse to the earth's field were compared with the deflections produced by oscillating the calibration cylinder transverse to the earth's field. Hence the experiment as a whole may be looked upon as a comparison of the electromotive forces produced in the effect cylinder itself by the two types of oscillation, rotary oscillation around the axis, and transverse oscillation perpendicular to the axis in such a way as to cut the earth's magnetic field. We may now proceed to an elementary theory of the experiment.

If a longitudinal acceleration a is applied to a metallic conductor, the electrons within the conductor will tend to move relative to the main body of the metal as though the conductor were stationary and the electrons were acted on by the force

$$f = ma, \tag{1}$$

where m may be called the "effective mass" of the electron. On the other hand, if an electromotive force E is applied to a stationary metallic conductor of length l and uniform cross section, the electrons within the conductor will be acted on by the force

$$f = (E/l)e, \tag{2}$$

where e is the charge of one electron. Since the "fictitious" force given by Eq. (1) and the "real" force given by Eq. (2) both tend to make the electrons move relative to the main body of the metal, it is evident that they may be equated in order to get an expression for the electromotive force produced by the longitudinal acceleration of a metallic conductor. We obtain, for the electromotive force E, produced in a metallic conductor of length l, by an acceleration a the expression

$$E = (m/e)la. \tag{3}$$

Let us now consider the rotary oscillations of the effect cylinder around its axis. At any radius r we may evidently write for the instantaneous acceleration the expression

$$a = 4\pi^2\nu^2\theta_e r \sin 2\pi\nu t, \tag{4}$$

where ν is the frequency of harmonic oscillation and θ_e is half the angular amplitude of oscillation. Substituting in Eq. (3) and taking the length of the conductor at the radius in question as $2\pi r$, we obtain

$$E_e = 8\pi^3\nu^2r^2(m/e)\theta_e \sin 2\pi\nu t \tag{5}$$

as an expression for the electromotive force around a current sheet located in the cylinder at the radius r.

Let us now compare this electromotive force with the electromotive force produced by the transverse oscillation of the cylinder in the earth's field used in calibrating. If θ_c is the half angular amplitude of transverse oscillation, we may write for the maximum flux through a current sheet of radius r, the expression

$$\phi_{max} = \pi r^2 H \sin \theta_c = \pi r^2 H\theta_c \text{ (for small amplitudes)}, \tag{6}$$

where H is total intensity of the earth's field; hence for harmonic oscillations of frequency ν, the electromotive force produced in carrying out the calibration is

$$E_c = 2\pi^2\nu r^2 H\theta_c \sin 2\pi\nu t. \tag{7}$$

Dividing Eq. (5) by (7), we obtain for the ratio of the two electromotive forces

$$\frac{E_e}{E_c} = \frac{4\pi\nu}{H}\frac{m}{e}\frac{\theta_e}{\theta_c}, \tag{8}$$

or solving for the thing of interest, namely the ratio of the effective mass of the electron to its charge, we obtain

$$\frac{m}{e} = \frac{H}{4\pi\nu}\frac{E_e}{E_c}\frac{\theta_c}{\theta_e}. \tag{9}$$

This is the equation which we shall use in calculating our experimental results. It will be noted that the radius r of the particular current sheet has dropped out so that E_e/E_c may be taken as the ratio of the total electromotive forces produced by the rotary oscillation and transverse oscillation of the effect cylinder.

IV. The Experimental Results

The master calibration.—In carrying out the actual experiments, a comparison was made of the galvanometer deflections produced by the rotary oscillation of the effect cylinder and the transverse oscillation of a much thinner walled calibration cylinder. For this reason, in order to use Eq. (9), it was necessary to carry out a master calibration comparing the electromotive forces produced by the transverse oscillation of the effect cylinder and the calibration cylinder.

To do this, at the completion of the regular runs, the torsion rod was cut off short on both sides of the effect cylinder, and one end clamped to the north face of the pier, so that the cylinder was perpendicular to the earth's magnetic field and had a natural period of vibration the same as that of its rotary oscillations. Arrangements were made to drive the cylinder with the same air engine used for producing rotary oscillations, and connections were made with a light silk cord to drive the calibration cylinder. The amplitudes of oscillation were measured with the help of mirrors fastened to the cylinders so as to reflect the image of an electric light filament on to a screen.

The results for both the 1/16″ and the 1/32″ cylinder are given below. Readings of the galvanometer deflection from the effect cylinder and from the calibration cylinder were made alternately, no readjustment of the filament heating currents in the amplifier being made between a given pair of readings. The filament heating current in the last stage was set considerably lower than usual in order to keep the deflection on the scale.

Effect Cylinder, Coil No. II Distance Mirror to Scale 137.5 Inches			1/16″ Calibration Cylinder, Coil No. I Distance Mirror to Scale 130.5 Inches		
Galvanometer Deflection mm	Amplitude of Oscillation mm	Ratio of Deflection to Amplitude	Galvanometer Deflection mm	Amplitude of Oscillation mm	Ratio of Deflection to Amplitude
215	34.8	6.18	38	25.5	1.490
203	31.8	6.38	49.5	33.5	1.477
240	39.3	6.11	44.5	30.5	1.459
226	34.8	6.495	42.5	27.5	1.545
207	30.8	6.72	39	24.0	1.625
		31.885			7.596

Hence the ratio of the deflection produced by the effect cylinder to that produced by the same oscillation of the 1/16″ calibration cylinder is $R = (31.885/7.596)(137.5/130.5) = 4.422$.

The corresponding ratio in the case of the 1/32″ calibration cylinder came out 7.86.

For the same amplitude of oscillation and hence for the same electromotive force applied to each of the primaries, the conductances of the three primaries stood in the ratio 1 to 2 to 16 while the galvanometer deflections were in the ratio 1 to 1.78 to 7.86. These figures show that the transformer system did not act as a pure potential device, but that there was a dissipation of energy in the secondary circuit, which may have been partly due to poor insulation in the secondary coils.

The regular runs.—In our discussion of the theory of the experiment, we derived the following equation:

$$\frac{m}{e} = \frac{H}{4\pi\nu}\frac{E_e}{E_c}\frac{\theta_c}{\theta_e}, \tag{9}$$

connecting the value of the desired ratio of mass to charge of the electron, with experimentally determinable quantities.

For H, the intensity of the earth's magnetic fields, we shall substitute the value 0.57963 gauss which was kindly determined for us by the U. S. Coast and Geodetic Survey with an instrument mounted on the pier near the location of the cylinders. (The value of H a few rods south of the pier was found to be 0.57634.)

The value of the frequency ν was found by attaching a stylus to the torsion rod so that it would mark on a strip of smoked paper drawn past it, a pendulum being also arranged to send a spark, at known intervals, from the stylus through the paper. The value of ν determined in this way was 18.9 per second.

The value of E_e/E_c, the ratio of the electromotive forces produced by the rotary oscillation and transverse oscillation of the effect cylinder, will be taken as G_e/G_cR, where G_e and G_c are the galvanometer deflections from the effect cylinder and the calibration cylinder and R is the ratio determined for these cylinders by the master calibration.

The value of θ_e, the half amplitude of oscillation of the effect cylinder, was read directly in degrees on a scale placed concentric with the rotating cylinder. The value of θ_c, the half amplitude of oscillation of the calibration cylinder, was determined by measuring the amplitude of oscillation of a ray of light from a mirror fastened so as to rock with the calibration cylinder. The value of θ_c in degrees will be taken as 57.30 $d/4l$, where d is the total width of the image on the screen during oscillation, corrected for the original width when stationary, and l is the distance from the mirror to scale.

Substituting the above values into Eq. (9) we obtain

$$\begin{aligned} &\text{For the } 1/16'' \text{ calibration cylinder: } m/e = 7.907 \times 10^{-3}(G_e d/G_c\theta_e l).\\ &\text{For the } 1/32'' \text{ calibration cylinder: } m/e = 4.448 \times 10^{-3}(G_e d/G_c\theta_e l).\end{aligned} \tag{10}$$

In carrying out the actual measurements, one observer controlled the operation of the air engine and read the amplitude of oscillation of the effect cylinder, a second observer inside the darkened observation house observed the amplitude of the beam of light reflected from the mirror on the calibration cylinder, and a third observer adjusted the filament heating currents, read the galvanometer deflections, and recorded the results.

The endeavor was made to obtain simultaneous readings of galvanometer deflection and amplitude of oscillation, and heating currents were not readjusted in the interval between a reading on the effect cylinder and the corresponding reading on the calibration cylinder. Eighty-six measurements were made in all in groups of six or seven. In the first fifty-six measurements, the readings were made in the order: effect, calibration, effect, calibration, etc. In the remaining thirty measurements, they were made in the superior order: effect, calibration, calibration, effect, effect, calibration, etc.

Owing to accidental electromagnetic disturbances, the galvanometer was always in oscillation when connected through the amplifier with one of the coils. This accidental effect was somewhat decreased by specially earthing the cylinders through a wire connected with the earthing wire from the amplifier, instead of relying merely on the connection through the concrete pier. In the first forty-four measurements the cylinders were not earthed, in the remaining forty-two they were earthed. For each group of measurements, readings were made of this accidental effect when the cylinders were not oscillating in order that a correction might be made for it. In the absence of detailed knowledge as to the nature of this accidental effect, the correction was made by simply subtracting from the total galvanometer deflection observed while the cylinder was oscillating, the galvanometer deflection when the cylinder was stationary.

Experimental values for a typical run.—In order to give an idea of the nature of the experimental results, the values obtained in the second group of six measurements are given below as fairly typical.

August 17, 1922, 10:55 A.M.
Distance from mirror to scale, l = 3,468 mm.
Effect Coil No. II., Calibration Coil No. I., 1/16″ Calibration Cylinder.

θ_e (deg.)	G_e (mm)	d (mm)	G_c (mm)	$m/e \times 10^8$
0	9.5	0	7	——
17	23	4.0	180	4.19
21	33	5.1	212	6.35
22.5	40	5.3	260	6.48
24	38	5.8	267	6.03
29	49	6.3	285	7.04
12	16	2.3	127	2.37

The values of m/e in the last column of the above table were calculated from Eq. (10). Before making the calculations, the galvanometer deflections were corrected by subtracting the deflection for zero amplitude.

Average value of mass divided by charge.—The average value of m/e

for the eighty-six measurements was 5.18×10^{-8}, with an average deviation of 1.33×10^{-8}. The average deviation divided by the square root of the number of observations was 0.14×10^{-8}.

V. Critique of the Experimental Work

In order to estimate the value of the results obtained above and in order to plan for more accurate work in the future some consideration of the various possible sources of error will not be out of place.

Effect of accidental oscillation transverse to the earth's field.—Limitations of time made it impossible for us to arrange a satisfactory neutralization of the earth's magnetic field in the space surrounding the effect cylinder. This made it necessary for us to consider the electromotive forces which might be produced by accidental transverse oscillations of the cylinder in this field.

In order to make the effect of such oscillations as small as possible we attempted to make the axis of the effect cylinder as nearly parallel to the direction of the earth's magnetic field as possible. However, since the declination may easily change by 30 minutes between ten o'clock in the morning and four o'clock in the afternoon, no exact parallelism was possible.

To investigate the actual magnitude of the accidental effects which might have been produced, we carried out a special test at the close of our experiments. After the torsion rod had been cut off short on both sides of the effect cylinder, one end of the torsion rod was clamped to the north face of the pier so that the effect cylinder was parallel to its running alignment and so that the cylinder would oscillate transversely with the same frequency as was used in the regular runs. With a total oscillation of about 0.002 radian, we obtained a galvanometer deflection of 54 mm with the galvanometer at its best tuning and the filament currents as usual. This deflection was thus of the same order of magnitude as the galvanometer deflections which were measured in the regular experiments. Since 0.002 radian would correspond to the large motion of 0.01″ in each bearing and since it is improbable that accidental transverse oscillations would consist of a single component having the same frequency as the rotary oscillation, we are inclined to believe that the accidental effect in question was considerably smaller than the main effect. It must be admitted, however, that this accidental effect might have had a serious influence on our results.

Attempts were also made to carry out the experiments with the earth's field neutralized. In the time available, however, we were unable to arrange to reduce the total intensity of the earth's field without at the same time introducing lack of homogeneity, and under these conditions we apparently got very erratic electromotive forces due to eddy currents in the oscillating cylinder.

Effect of centrifugal action.—Another source of error which must be investigated lies in the action of centrifugal force in making the effect cylinder alternately larger and smaller, and thus changing the flux through the cylinder. Taking account of the density and elastic modulus of copper, it can be calculated that the electromotive force produced in this way would be about 6 per cent of the electromotive force due to the effect. This accidental electromotive force, however, has twice the frequency of the electromotive force due to the effect and hence can be entirely neglected since we showed by special experiments that the vibration galvanometer had no appreciable sensitivity at frequencies other than those for which it was tuned.

Effect of motion of coil.—Any oscillation of the large coil surrounding the effect cylinder would of course have been very serious. After experimenting with various ways of fastening the coil in position, we came to the conclusion that our final strapping of the coil to the concrete pier as firmly as possible had eliminated serious effects of the kind in question.

Correction for zero effect.—Probably the most serious errors in the experiment were due to the large deflection of the galvanometer even when the apparatus was stationary. This zero deflection was usually about 9 to 10 mm when the cylinder was not specially earthed and 4 to 5 mm when the cylinder was connected to the earthing wire from the amplifier. Since the total deflections obtained from the effect were, after correction, usually of the order of 20 to 30 mm, it is evident that the zero effect is very serious.

The correction was arbitrarily made by subtracting the zero deflection from the total deflection obtained while running. Further study of the nature of the accidental forces which lead to the zero effect would be necessary in order to justify such a method of correction. Such a further study could perhaps be made by some oscillographic method. It is interesting to note that the zero effect could not be greatly reduced either by "tuning" out or by connecting a compensating coil so as to "buck" the effect coil. Electrostatic shielding might be helpful.

Evidence that the method of correcting for the zero deflection was not entirely correct is shown by the fact that the average value of m/e for forty-four runs in which the cylinders were not specially earthed was 5.97×10^{-8} while it was 4.35×10^{-8} for the forty-two runs in which the zero effect had been decreased by the special earthing.

VI. Discussion and Conclusion

It is felt that the work presented above may be regarded as another fairly satisfactory demonstration of the production of electromotive forces by the acceleration of a metallic conductor and as indicating again that the mass of the carrier in metals is about the same as the mass of an electron in free space. The new work taken by itself alone is perhaps not as convincing as the work of Tolman and Stewart, because of the greater complexity of the apparatus, because of the fact that time did not permit a satisfactory neutralization of the earth's field, and because further developments of the method would be necessary in order to show that the direction of the effect is that predicted on the basis of a mobile *negative* carrier. Our total certainty as to the reality of the effect is, however, greatly increased by the fact that two such widely divergent methods have led to concordant results.

Values of m/e obtained in different ways are given below, in grams per abcoulomb.

m/e in free space	5.66×10^{-8}	(cathode rays)
m/e in copper	6.24×10^{-8}	(Tolman and Stewart)
m/e in silver	6.73×10^{-8}	(Tolman and Stewart)
m/e in aluminum	6.50×10^{-8}	(Tolman and Stewart)
m/e in copper	5.18×10^{-8}	(Tolman, Karrer and Guernsey).

It is evident that our data are not yet accurate enough to determine whether the mass of the electron in a metal is precisely the same as that in free space or not.

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